

COMPLEX NETWORKS

Centrality measures

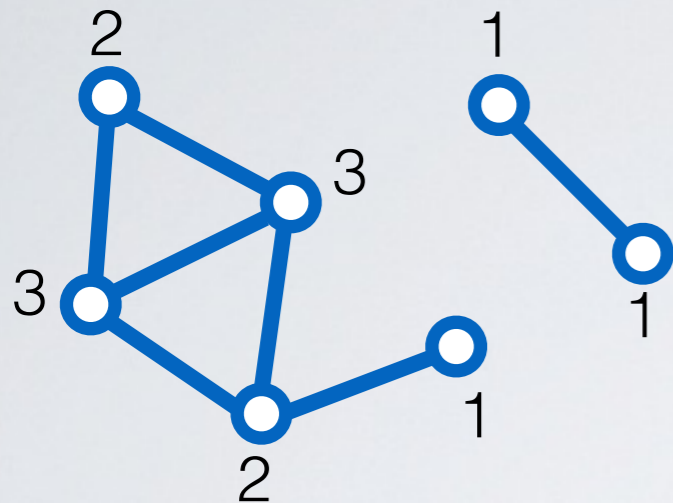
NODE

- We can measure nodes importance using so-called **centrality**.
- Poor terminology: nothing to do with being central in general
- Usage:
 - Some centralities have straightforward interpretation
 - Centralities can be used as *node features* for machine learning on graph
 - (Classification, link prediction, ...)

Degree centrality - recap

Number of connections of a node

- Undirected network



$$k_i = A_{i1} + A_{i2} + \dots + A_{iN} = \sum_j^N A_{ij}$$

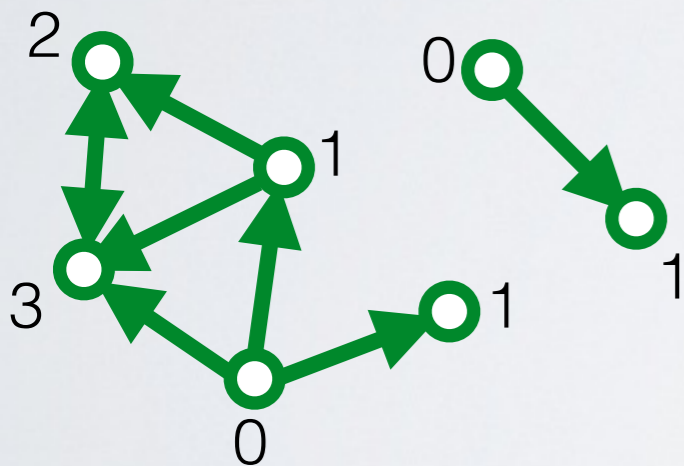
$$m = \frac{\sum_i k_i}{2} \quad \text{where} \quad m = |E|$$

mean degree

$$\langle k \rangle = \frac{1}{N} \sum_i^N k_i$$

[illegible]

- Directed network



In degree

$$k_i^{in} = \sum_j^N A_{ij}$$

Out degree

$$k_j^{out} = \sum_i^N A_{ij}$$

$$m = \sum_i^N k_i^{in} = \sum_j^N k_j^{out} = \sum_{ij} A_{ij}$$

$$\langle k^{in} \rangle = \frac{1}{N} \sum_{i=1}^N k_i^{in} = \frac{1}{N} \sum_{j=1}^N k_j^{out} = \langle k^{out} \rangle$$

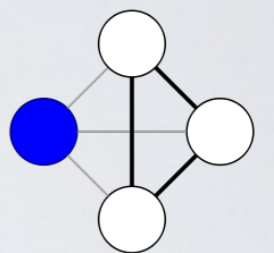
[illegible][illegible]

NODE DEGREE

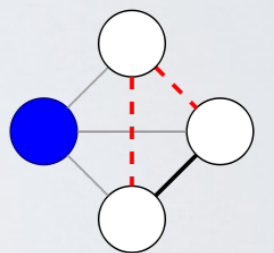
- **Degree:** how many neighbors
- Often enough to find important nodes
 - Main characters of a series talk with the more people
 - Largest airports have the most connections
 - ...
- But not always
 - Facebook users with the most friends are spam
 - Webpages/wikipedia pages with most links are simple lists of references
 - ...

NODE CLUSTERING COEFFICIENT

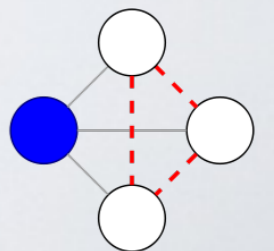
- **Clustering coefficient:** density of neighborhood
- Tells you if the neighbors of the node are connected
- Be careful!
 - Degree 2: value 0 or 1
 - Degree 1000: Not 0 or 1 (usually)
 - Ranking them is not meaningful
- Can be used as a proxy for “communities” belonging:
 - If node belong to single group: high CC
 - If node belong to several groups: lower CC



$$c = 1$$



$$c = 1/3$$



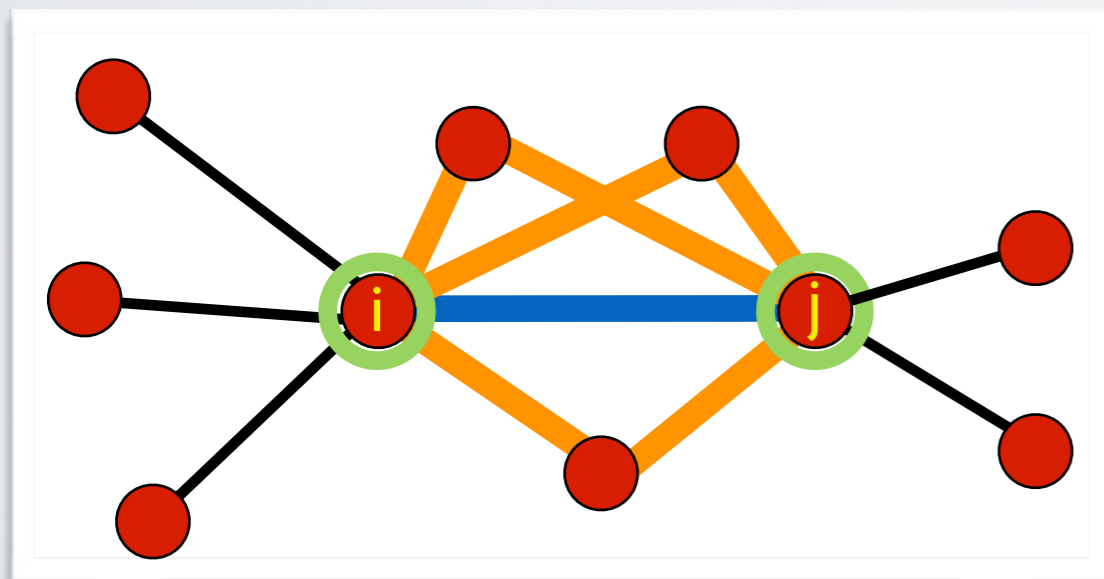
$$c = 0$$

Link clustering coefficient: Overlap

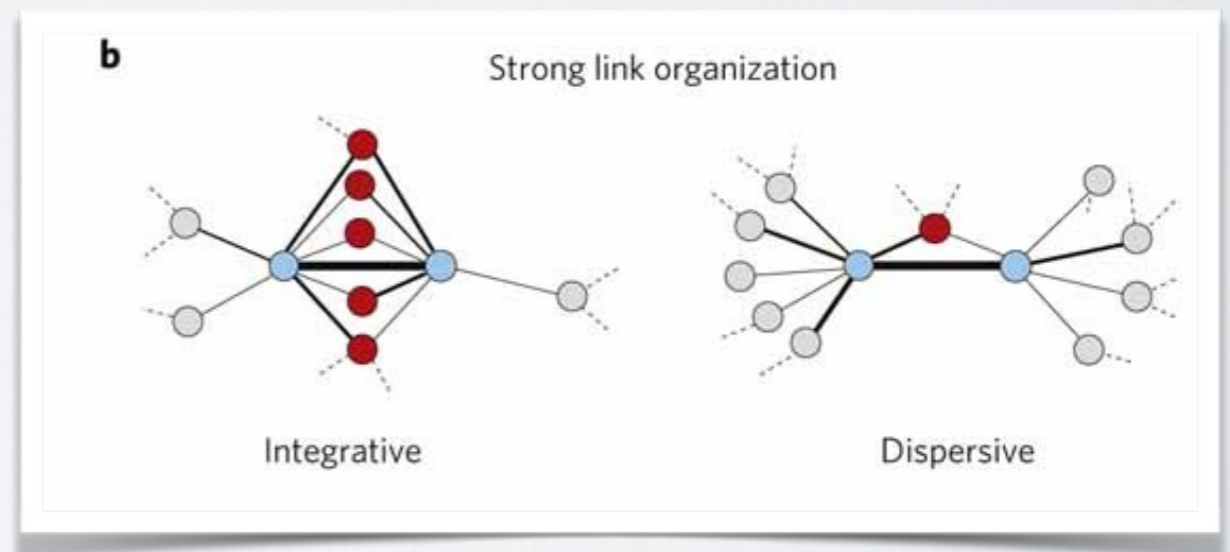
- Link property
- Fraction of common neighbors of a connected pair
- Jaccard Coefficient of neighborhoods

Edge Clustering C^e of an edge (u, v) is the fraction of the neighbors of at least one of the two nodes which are neighbors of both of them, i.e.,

$$C^e(u, v) = \frac{|N_u \cap N_v|}{|N_u \cup N_v| - 2}$$



$$C^e(i, j) = \frac{3}{8}$$

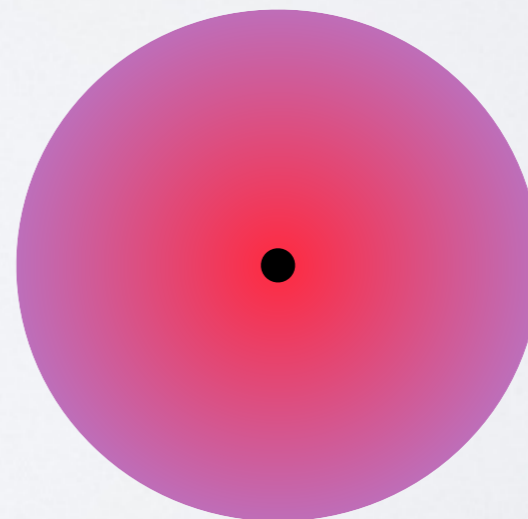
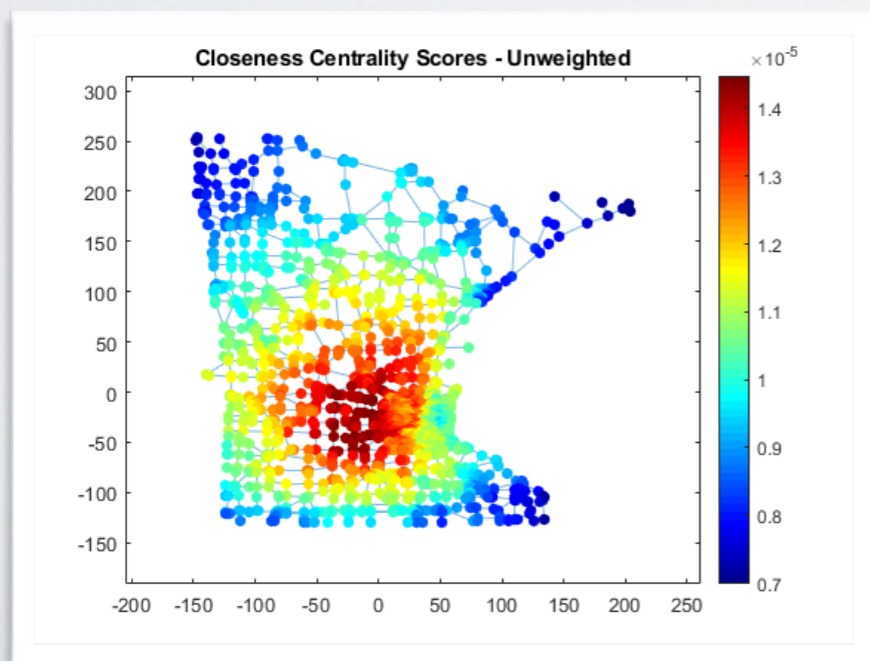


Pajevic, S., & Plenz, D. (2012). The organization of strong links in complex networks. *Nature Physics*, 8(5), 429-436.

FARNESS, CLOSENESS
HARMONIC CENTRALITY

FARNESS, CLOSENESS

- How close the node is to all other nodes
- Parallel with the center of a figure:
 - Center of a circle is the point of shorter average distance to any points in the circle



FARNESS, CLOSENESS

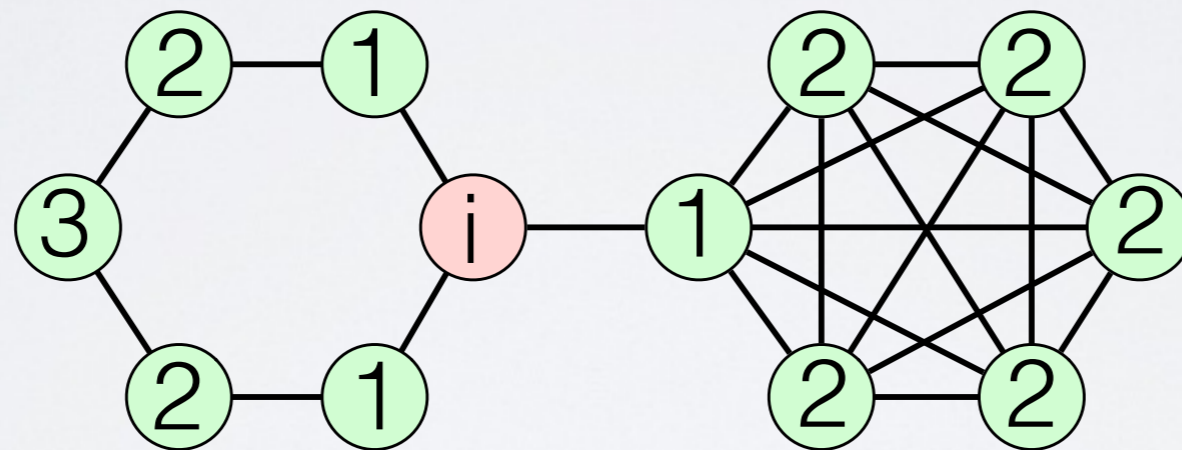
Farness: Average distance to all other nodes in the graph

$$\text{Farness}(u) = \frac{1}{N - 1} \sum_{v \in V \setminus u} \ell_{u,v}$$

CLOSENESS CENTRALITY

Closeness: Inverse of the farness, i.e., how close the node is to all other nodes in term of shortest paths.

$$\text{Closeness}(u) = \frac{N - 1}{\sum_{v \in V \setminus u} \ell_{u,v}}$$



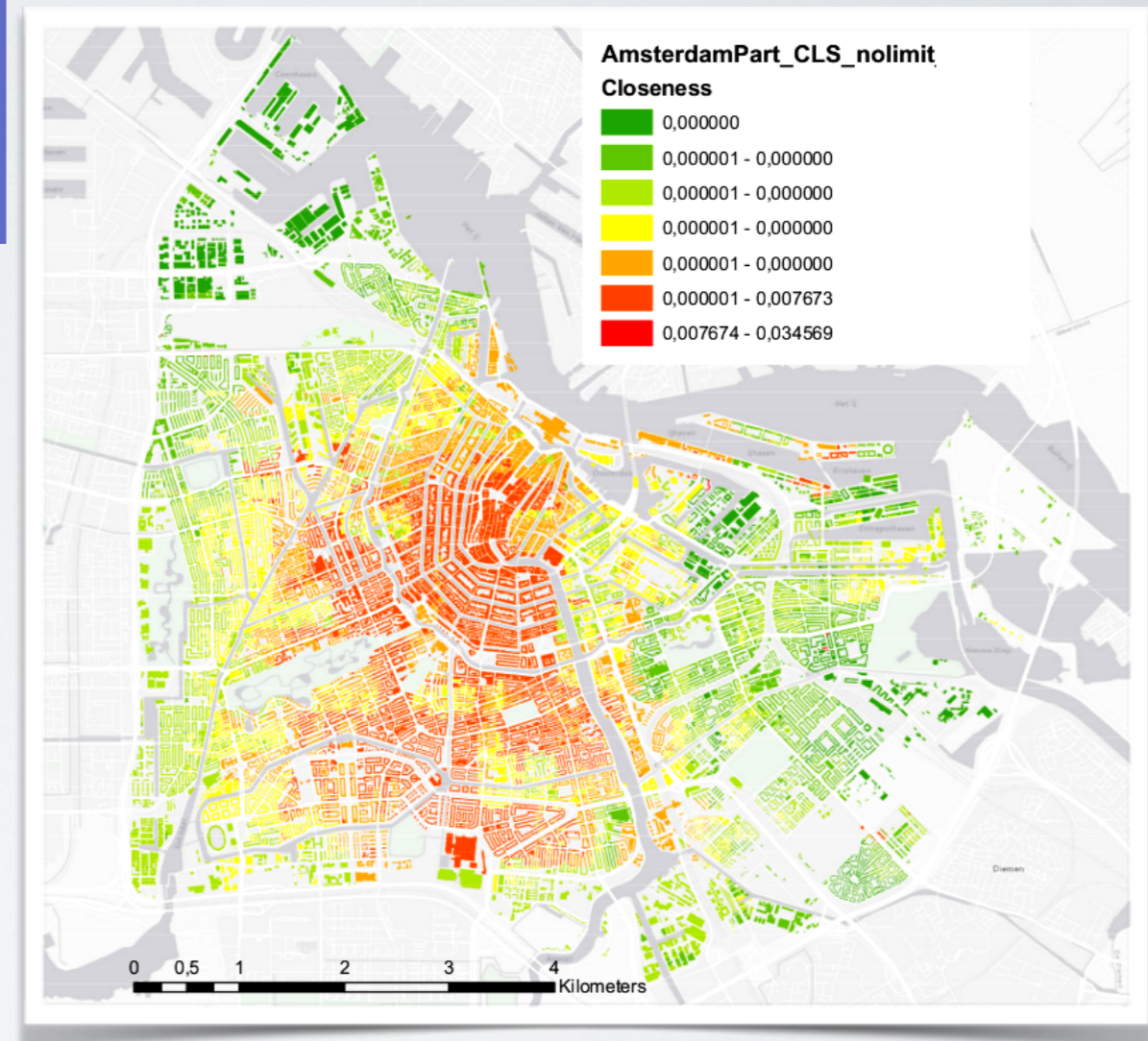
$$C_{cl}(i) = \frac{12 - 1}{(3 \times 1 + 7 \times 2 + 1 \times 3)} = \frac{11}{20} = 0.55$$

CLOSENESS CENTRALITY

Closeness: Inverse of the farness, i.e., how close the node is to all other nodes in term of shortest paths.

$$\text{Closeness}(u) = \frac{N - 1}{\sum_{v \in V \setminus u} \ell_{u,v}}$$

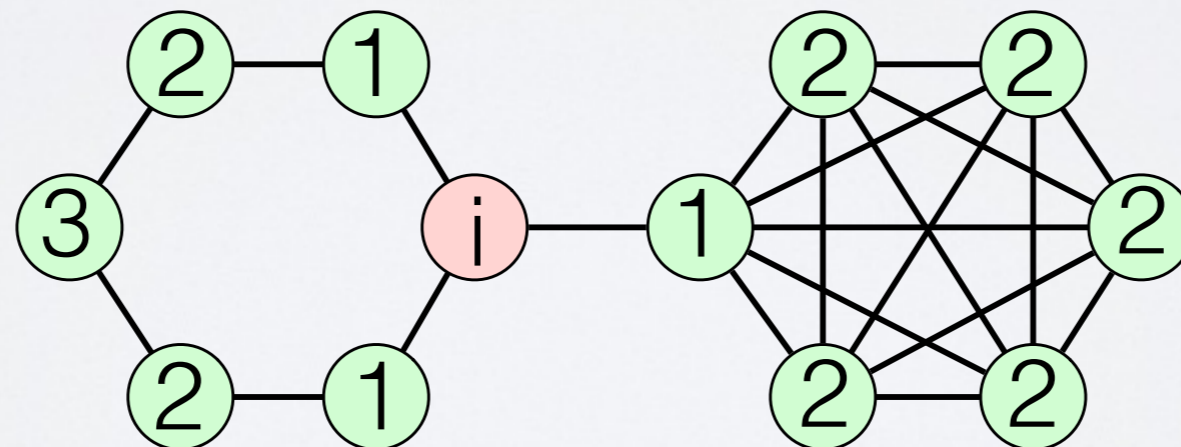
| =all nodes are at distance one



Harmonic Centrality

Harmonic centrality: A variant of the closeness defined as the average of the inverse of distance to all other nodes (Harmonic mean). Well defined on disconnected network with $\frac{1}{\infty} = 0$. Its interpretation is the same as the closeness.

$$\text{Harmonic}(u) = \frac{1}{N - 1} \sum_{v \in V \setminus u} \frac{1}{\ell_{u,v}}$$



$$C_h(i) = \frac{1}{12 - 1} \left(3 \times \frac{1}{1} + 7 \times \frac{1}{2} + 1 \times \frac{1}{3} \right) = \frac{41}{66} = 0.6212$$

KATZ CENTRALITY

- Measure of the influence potential of a node

$$C_{\text{Katz}}(u) = \sum_{\ell=1}^{\infty} \sum_{v=1}^N \alpha^{\ell} (A^{\ell})_{vu}$$

in which A^{ℓ}_{vu} means the number of paths of length ℓ from v to u , and $\alpha < \frac{1}{\lambda_i}$ a parameter smaller than the reciprocal of the largest eigenvalue of A , allowing to compute with matrix form:

$$C_{\text{Katz}}(u) = ((I - \alpha A^T)^{-1} - I) \vec{1}$$

KATZ CENTRALITY

$$C_{\text{Katz}}(i) = \sum_{k=1}^{\infty} \sum_{j=1}^n \alpha^k (A^k)_{ij}$$

connected pairs of nodes in distance k

attenuation factor to penalise influence by distance

Katz centrality of node i =

KATZ CENTRALITY

$$C_{\text{Katz}}(i) = \sum_{k=1}^{\infty} \sum_{j=1}^n \alpha^k (A^k)_{ij}$$

Repeat for all distances as long
As possible (convergence)

KATZ CENTRALITY

$$C_{\text{Katz}}(i) = \sum_{k=1}^{\infty} \sum_{j=1}^n \alpha^k (A^k)_{ij}$$

Sum for each other node **j**

KATZ CENTRALITY

$$C_{\text{Katz}}(i) = \sum_{k=1}^{\infty} \sum_{j=1}^n \alpha^k (A^k)_{ij}$$

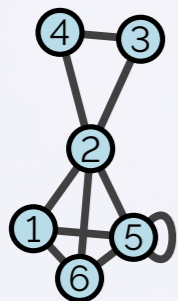
α is a parameter in $[0, 1]$.
Its strength decreases at
each iteration (increased distance)

KATZ CENTRALITY

$$C_{\text{Katz}}(i) = \sum_{k=1}^{\infty} \sum_{j=1}^n \alpha^k (A^k)_{ij}$$

Number of different paths from **i** to **j**
of length k

Graph



A - Adjacency Mat.

$$\begin{pmatrix} 0 & 1 & 0 & 0 & 1 & 1 \\ 1 & 0 & 1 & 1 & 1 & 1 \\ 0 & 1 & 0 & 1 & 0 & 0 \\ 0 & 1 & 1 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 & 1 & 1 \\ 1 & 1 & 0 & 0 & 1 & 0 \end{pmatrix}$$

A^2

$$\begin{pmatrix} 3 & 2 & 1 & 1 & 3 & 2 \\ 2 & 5 & 1 & 1 & 3 & 2 \\ 1 & 1 & 2 & 1 & 1 & 1 \\ 1 & 1 & 1 & 2 & 1 & 1 \\ 3 & 3 & 1 & 1 & 4 & 3 \\ 2 & 2 & 1 & 1 & 3 & 3 \end{pmatrix}$$

KATZ CENTRALITY

$$C_{\text{Katz}}(i) = \sum_{k=1}^{\infty} \sum_{j=1}^n \alpha^k (A^k)_{ij}$$

Sum of paths to all other nodes at each distance multiplied by a factor decreasing with distance

BETWEENNESS CENTRALITY

- Measure how much the node plays the role of a bridge
- Betweenness of u : fraction of all the shortest paths between all the pairs of nodes going through u .

$$C_B(v) = \sum_{s \neq v \neq t \in V} \frac{\sigma_{st}(v)}{\sigma_{st}}$$

with σ_{st} the number of shortest paths between nodes s and t and $\sigma_{st}(v)$ the number of those paths passing through v .

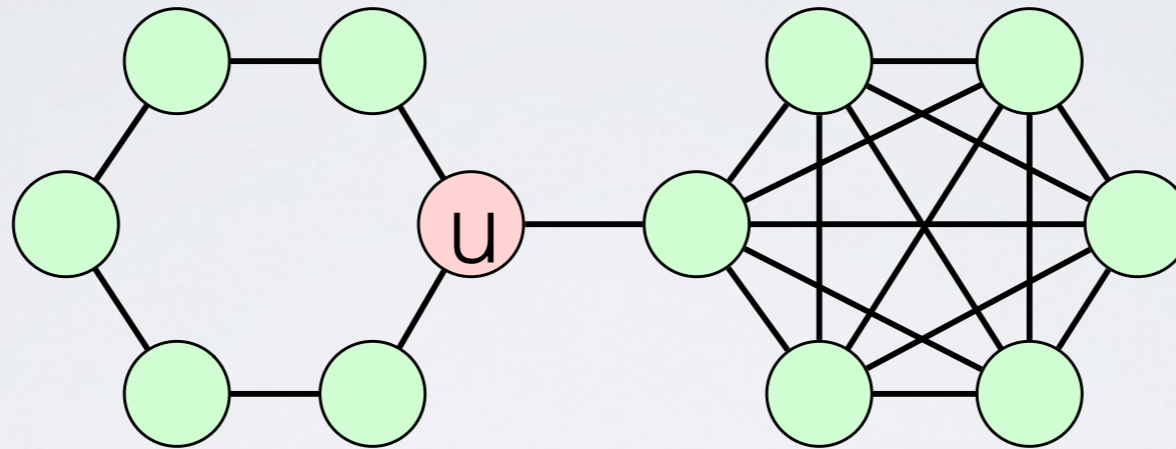
The betweenness tends to grow with the network size. A normalized version can be obtained by dividing by the number of pairs of nodes, i.e., for a

directed graph: $C_B^{\text{norm}}(v) = \frac{C_B(v)}{(N-1)(N-2)}$.

Betweenness Centrality

$$C_B(v) = \sum_{s \neq v \neq t \in V} \frac{\sigma_{st}(v)}{\sigma_{st}}$$

directed graph: $C_B^{\text{norm}}(v) = \frac{C_B(v)}{(N-1)(N-2)}$.



$$C_B(u) = 2 \frac{5 * 6 + 1 + \frac{1}{2} + \frac{1}{2}}{11 * 10} = \frac{64}{110}$$

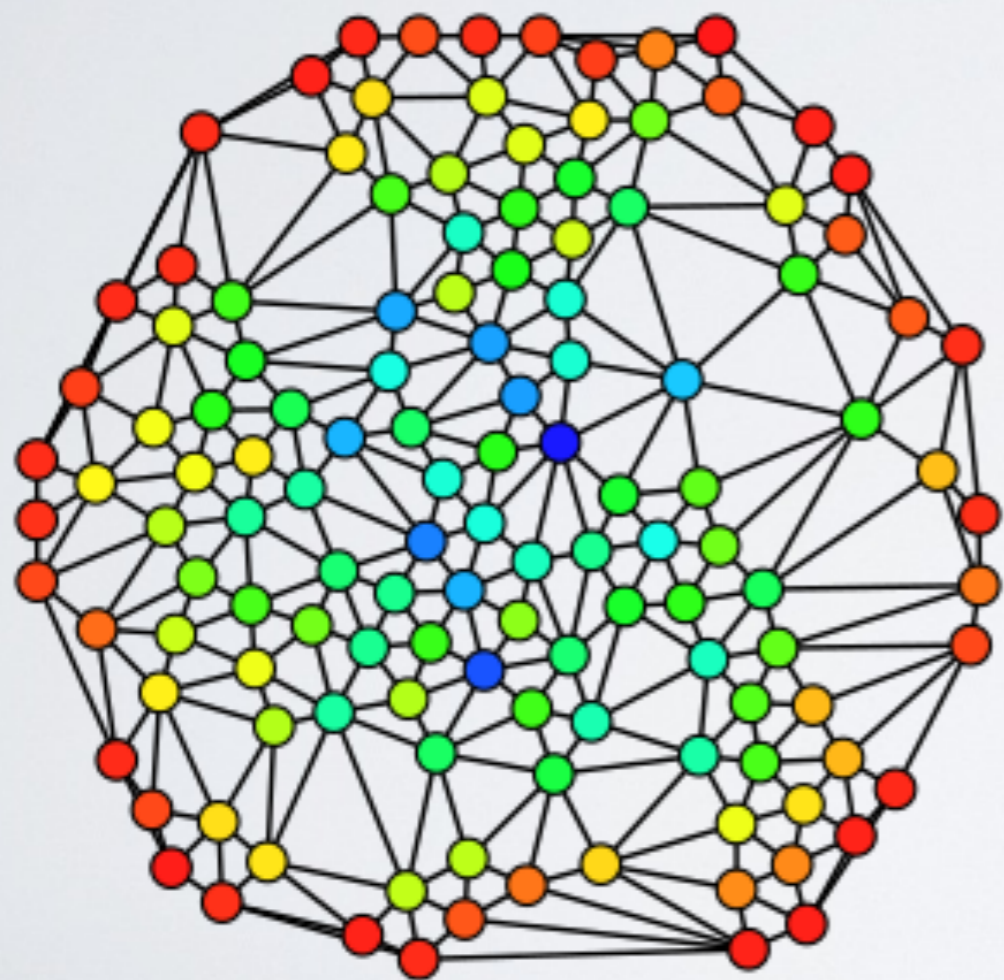
Exact computation:

Floyd-Warshall: $O(n^3)$ time complexity
 $O(n^2)$ space complexity

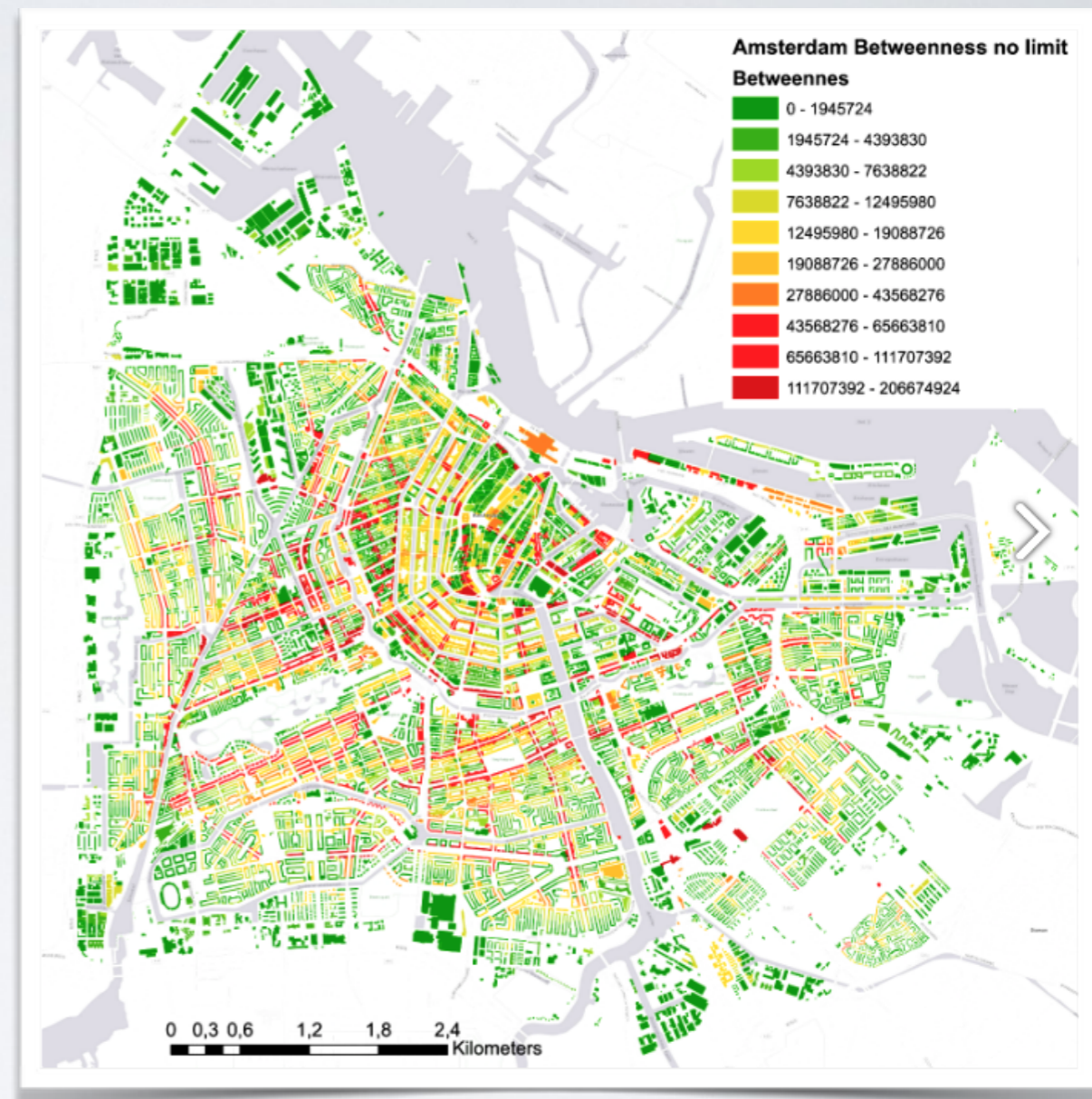
Approximate computation

Dijkstra: $O(n(m+n \log n))$ time complexity

BETWEENNESS CENTRALITY



(blue higher)



(red higher)

EDGE - BETWEENNESS

Same definition as for nodes

Can you guess the edge of highest betweenness in the European rail network?



RECURSIVE DEFINITIONS

RECURSIVE DEFINITIONS

- Recursive importance:
 - **Important nodes** are those connected **to important nodes**
- Several centralities based on this idea:
 - Eigenvector centrality
 - PageRank
 - ...

RECURSIVE DEFINITION

- We would like scores such as :
 - Each node has a score (centrality),
 - If every node “sends” its score to its neighbors, the sum of all scores received by each node will be equal to its original score

$$C_u^{t+1} = \frac{1}{\lambda} \sum_{v \in N_u^{in}} C_v^t \quad (1)$$

- With λ a normalisation constant

RECURSIVE DEFINITION

- This problem can be solved by what is called the *power method*:
 - 1) We initialize all scores to random values
 - 2) Each score is updated according to the desired rule, until reaching a stable point (after normalization)
- Why does it converge?
 - Perron-Frobenius theorem (see next slide)
 - \Rightarrow True for undirected graphs with a single connected component

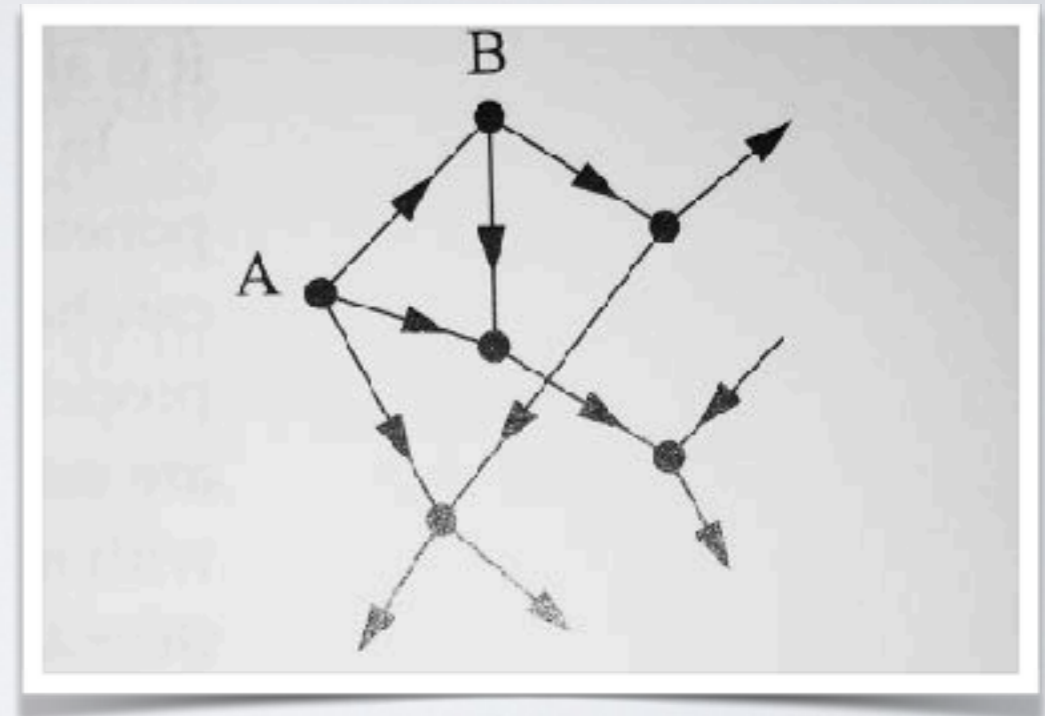
EIGENVECTOR CENTRALITY

- What we just described is called the Eigenvector centrality
- A couple eigenvector (x) and eigenvalue (λ) is defined by the following relation: $Ax = \lambda x$
 - x is a column vector of size n , which can be interpreted as the scores of nodes
- What Perron-Frobenius algorithm says is that the power method will always converge to the *leading eigenvector*, i.e., the eigenvector associated with the highest eigenvalue

Eigenvector Centrality

Some problems in case of directed network:

- Adjacency matrix is asymmetric
- 2 sets of eigenvectors (Left & Right)
- 2 leading eigenvectors
 - Use right eigenvectors : consider nodes that are pointing towards you



But problem with source nodes (0 in-degree)

- Vertex A is connected but has only outgoing link = Its centrality will be 0
- Vertex B has outgoing and an incoming link, but incoming link comes from A = Its centrality will be 0
- etc.

Solution: Only in strongly connected component

Note: Acyclic networks (citation network) do not have strongly connected component

PageRank Centrality

- Eigenvector centrality generalised for directed networks

PageRank

The Anatomy of a Large-Scale Hypertextual Web Search Engine

Brin, S. and Page, L. (1998) The Anatomy of a Large-Scale Hypertextual Web Search Engine. In: Seventh International World-Wide Web Conference (WWW 1998), April 14-18, 1998, Brisbane, Australia.

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Abstract

In this paper, we present Google, a prototype of a large-scale search engine which makes heavy use of the structure present in hypertext. Google is designed to crawl and index the Web efficiently and produce much more satisfying search results than existing systems. The prototype with a full text and hyperlink database of at least 24 million pages is available at <http://google.stanford.edu/>

PageRank Centrality

(Side notes)

-“We chose our system name, Google, because it is a common spelling of googol, or 10^{100} and fits well with our goal of building very large-scale search “

-“[...] at the same time, search engines have migrated from the academic domain to the commercial. **Up until now most search engine development has gone on at companies with little publication of technical details. This causes search engine technology to remain largely a black art and to be advertising oriented (see Appendix A). With Google, we have a strong goal to push more development and understanding into the academic realm.”**

-“[...], we expect that advertising funded search engines will be inherently biased towards the advertisers and away from the needs of the consumers.”

PageRank Centrality

(Side notes)



Sergey Brin received his B.S. degree in mathematics and computer science from the University of Maryland at College Park in 1993. Currently, he is a Ph.D. candidate in computer science at Stanford University where he received his M.S. in 1995. He is a recipient of a National Science Foundation Graduate Fellowship. His research interests include search engines, information extraction from unstructured sources, and data mining of large text collections and scientific data.



Lawrence Page was born in East Lansing, Michigan, and received a B.S.E. in Computer Engineering at the University of Michigan Ann Arbor in 1995. He is currently a Ph.D. candidate in Computer Science at Stanford University. Some of his research interests include the link structure of the web, human computer interaction, search engines, scalability of information access interfaces, and personal data mining.

PAGERANK

- 2 main improvements over eigenvector centrality:
 - In directed networks, problem of source nodes
 - => Add a constant centrality gain for every node
 - Nodes with very high centralities give very high centralities to all their neighbors (even if that is their only in-coming link)
 - => What each node “is worth” is divided equally among its neighbors (normalization by the degree)

$$C_u^{t+1} = \frac{1}{\lambda} \sum_{v \in N_u^{in}} C_v^t$$

=>

$$C_u^{t+1} = \alpha \sum_{v \in N_u^{in}} \frac{C_v^t}{k_v^{out}} + \beta$$

With by convention $\beta=1$ and α a parameter (usually 0.85) controlling the relative importance of β

PAGERANK

Matrix interpretation

Principal eigenvector of the “Google Matrix”:

First, define matrix S as:

- Normalization by columns of A
- Columns with only 0 receives $1/n$

-Finally, $G_{ij} = \alpha S_{ij} + (1 - \alpha)/n$

$$(a) \quad A = \begin{pmatrix} 0 & 1 & 1 & 0 & 0 \\ 1 & 0 & 1 & 1 & 0 \\ 0 & 1 & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \end{pmatrix}$$

$$(c) \quad S = \begin{pmatrix} 0 & 1/2 & 1/3 & 0 & 1/5 \\ 1 & 0 & 1/3 & 1/3 & 1/5 \\ 0 & 1/2 & 0 & 1/3 & 1/5 \\ 0 & 0 & 1/3 & 0 & 1/5 \\ 0 & 0 & 0 & 1/3 & 1/5 \end{pmatrix}$$

$$(e) \quad G = \begin{pmatrix} 0.03 & 0.455 & 0.313 & 0.03 & 0.2 \\ 0.88 & 0.03 & 0.313 & 0.313 & 0.2 \\ 0.03 & 0.455 & 0.03 & 0.313 & 0.2 \\ 0.03 & 0.03 & 0.313 & 0.03 & 0.2 \\ 0.03 & 0.03 & 0.03 & 0.313 & 0.2 \end{pmatrix}$$

PageRank - as Random Walk

Main idea: The PageRank computation can be interpreted as a Random Walk process with restart

Teleportation probability: the parameter α gives the probability that in the next step of the RW will follow a Markov process or with probability $1-\alpha$ it will jump to a random node

Pagerank score of a node thus corresponds to the probability of this random walker to be on this node after an infinite number of hops.

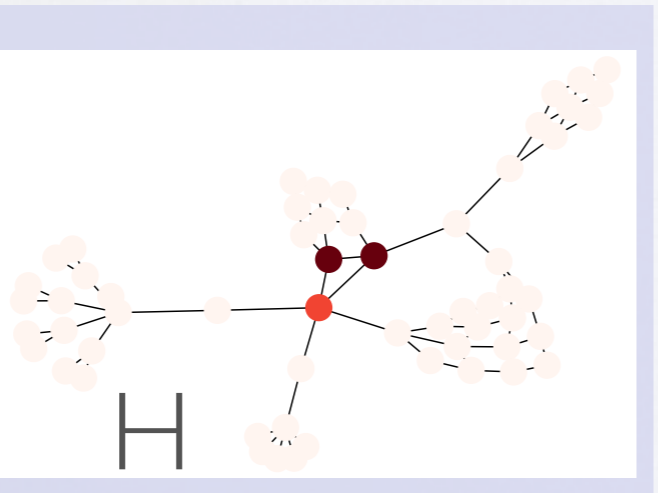
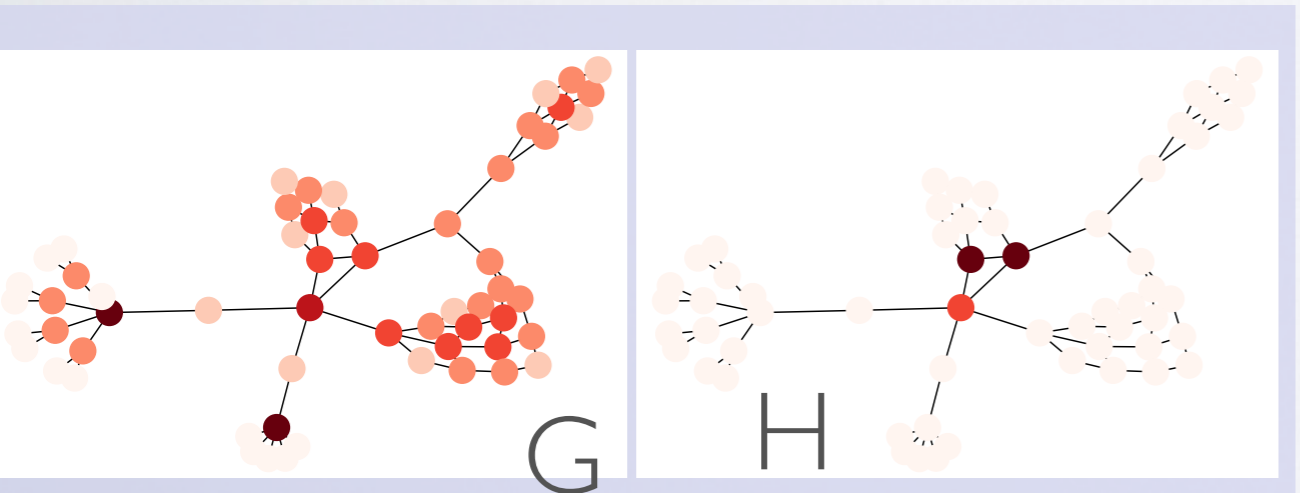
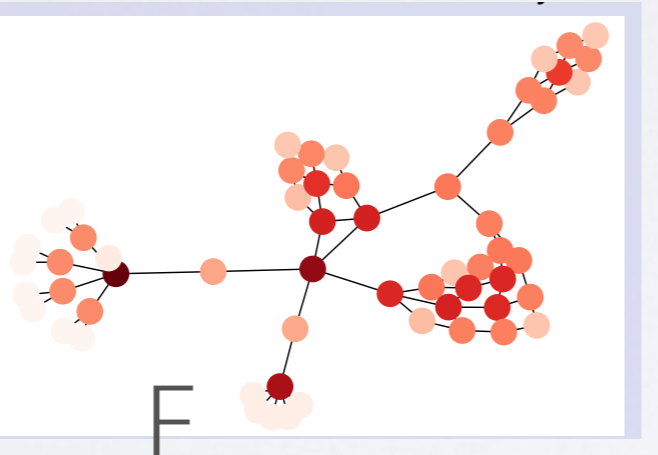
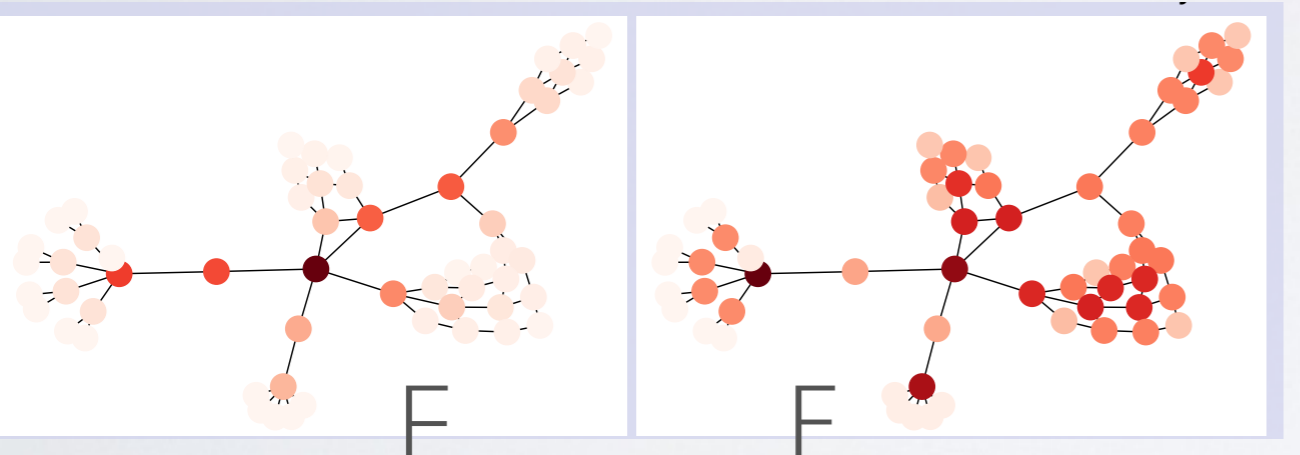
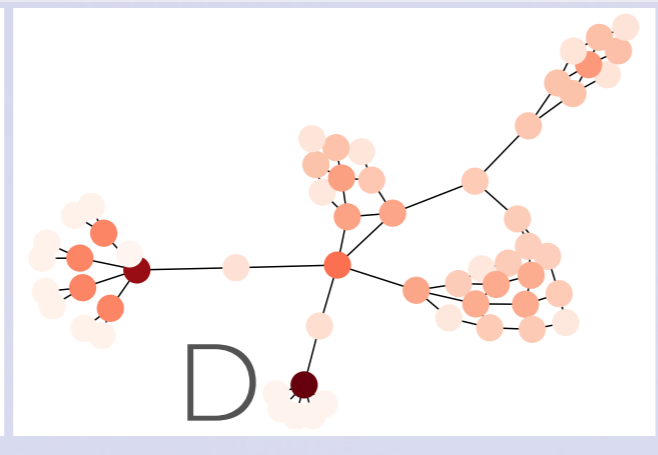
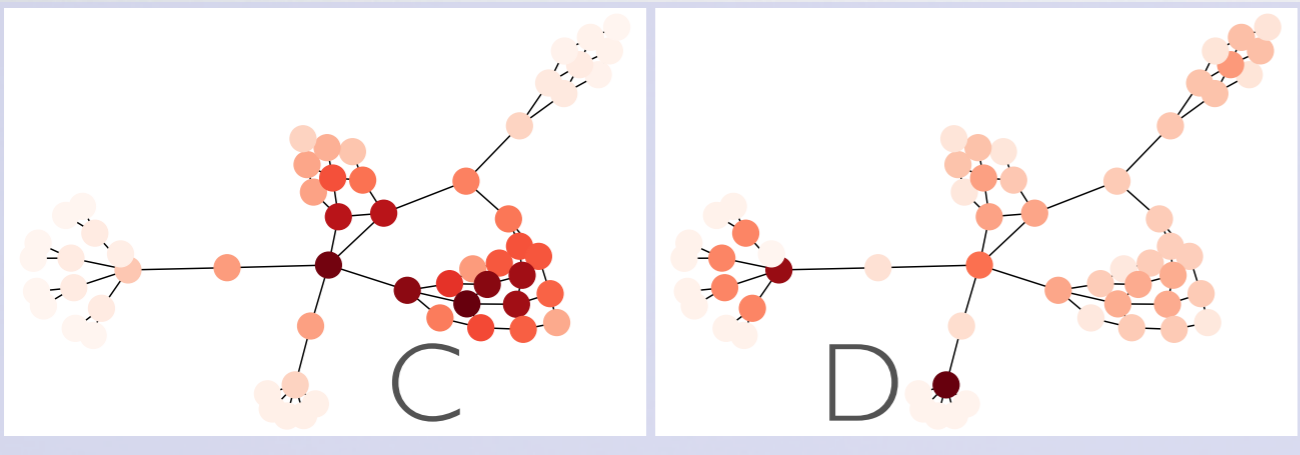
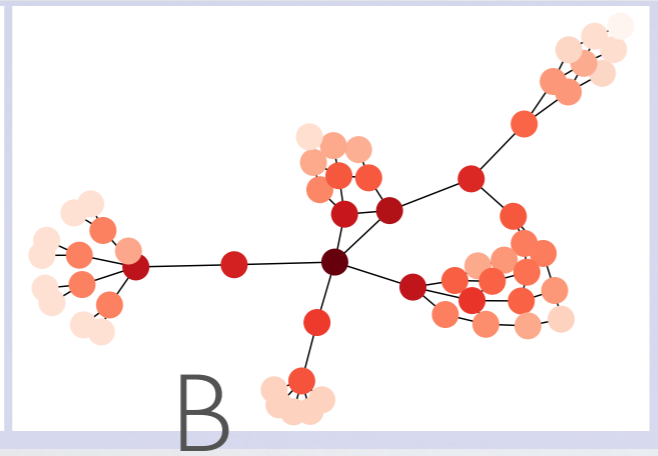
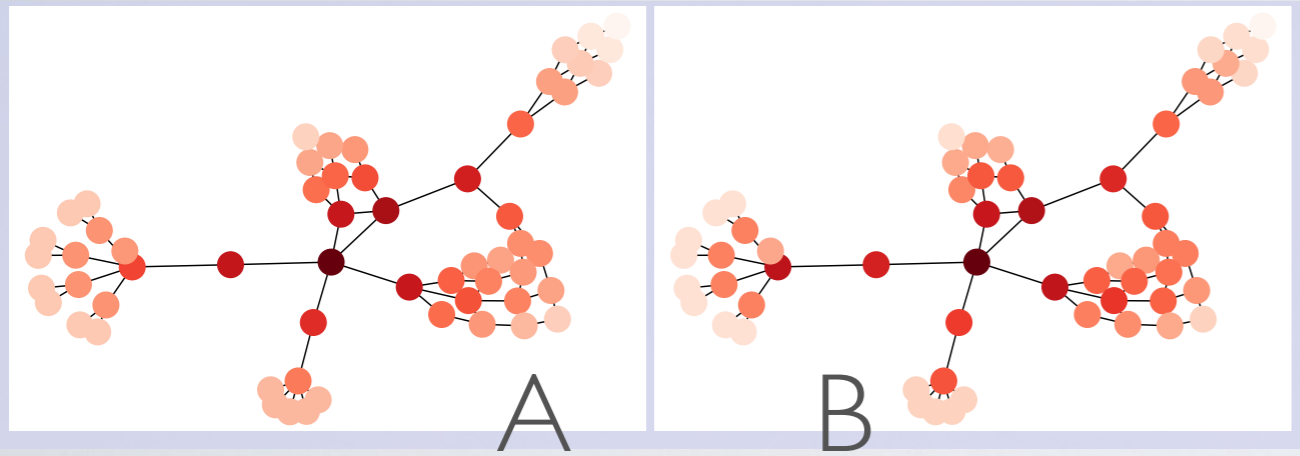
PAGERANK

- Then how do Google rank when we do a research?
- Compute pagerank (using the power method for scalability)
- Create a subgraph of documents related to our topic
- Of course now it is certainly much more complex, but we don't really know:
“Most search engine development has gone on at companies with little publication of technical details. This causes search engine technology to remain largely a black art” [Page, Brin, 1997]

OTHERS

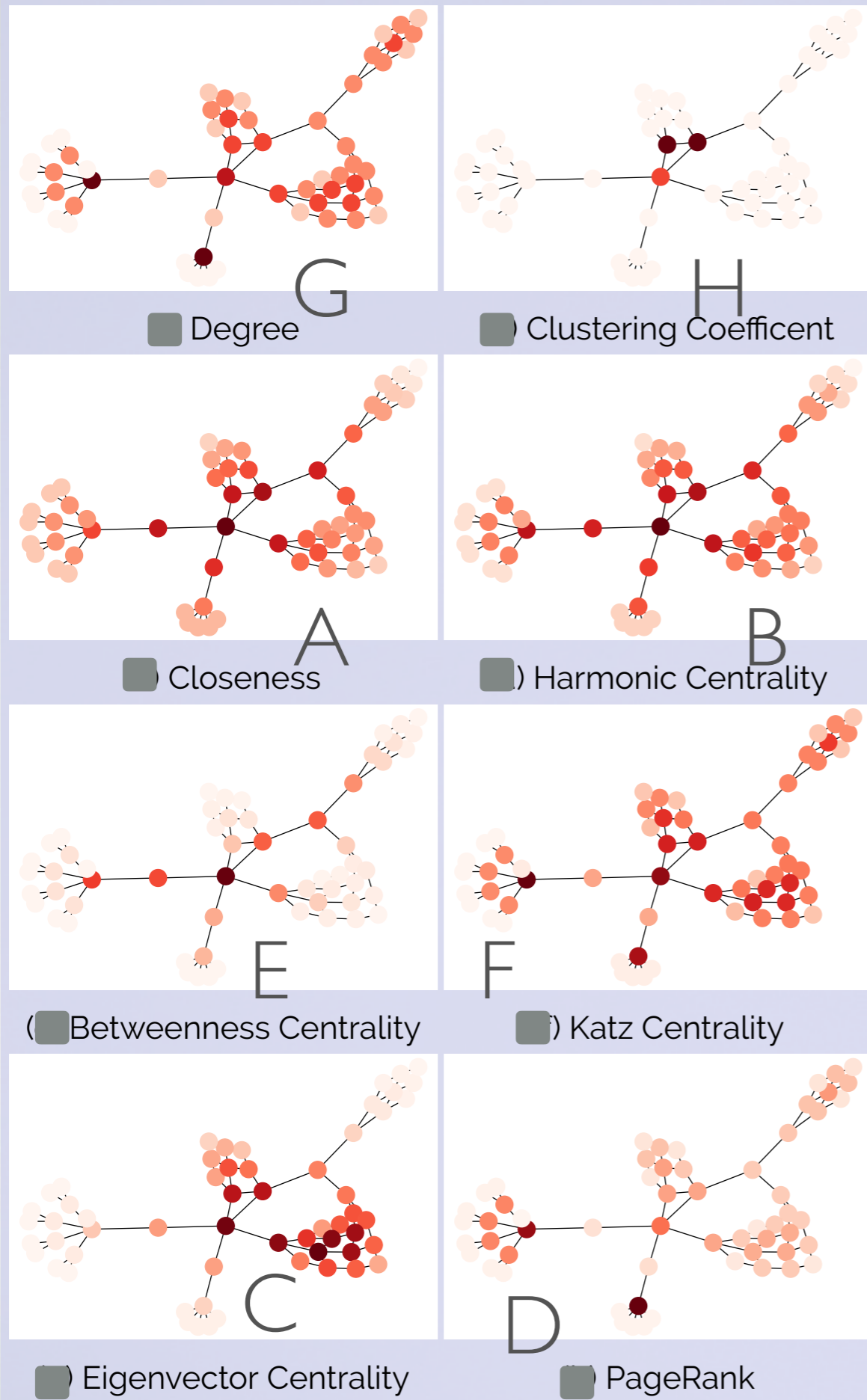
- Many other centralities have been proposed
- The problem is how to interpret them ?
- Can be used as supervised tool:
 - Compute many centralities on all nodes
 - Learn how to combine them to find chosen nodes
 - Discover new similar nodes
 - (roles in social networks, key elements in an infrastructure, ...)

Which is which ?

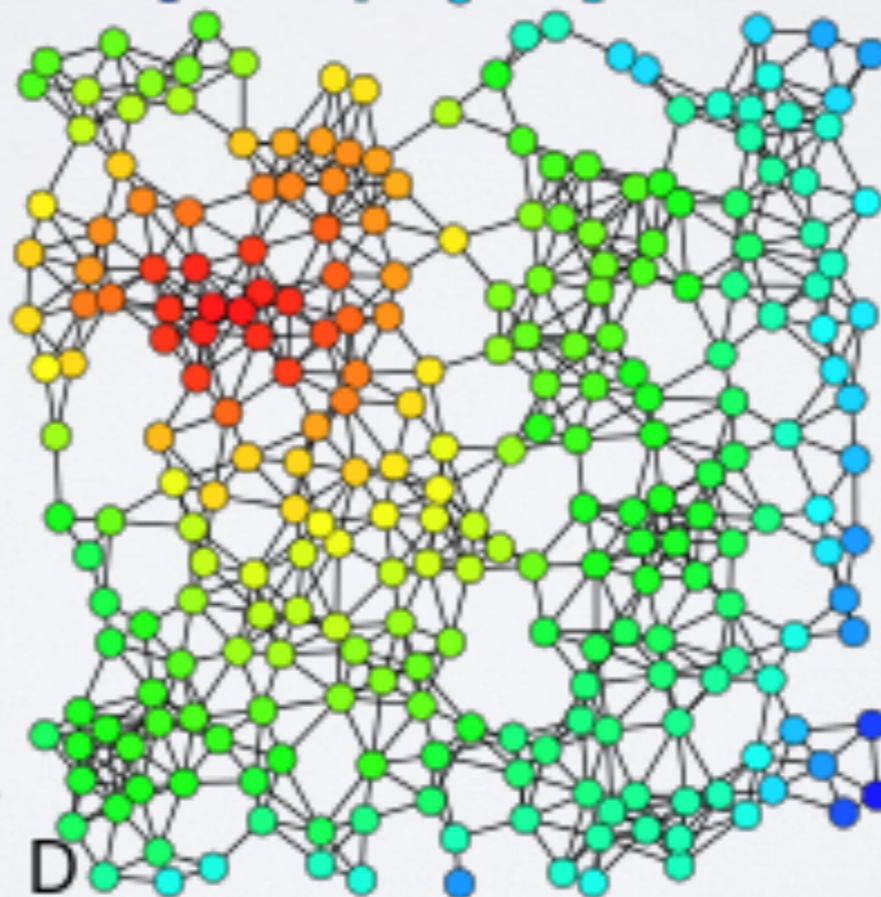
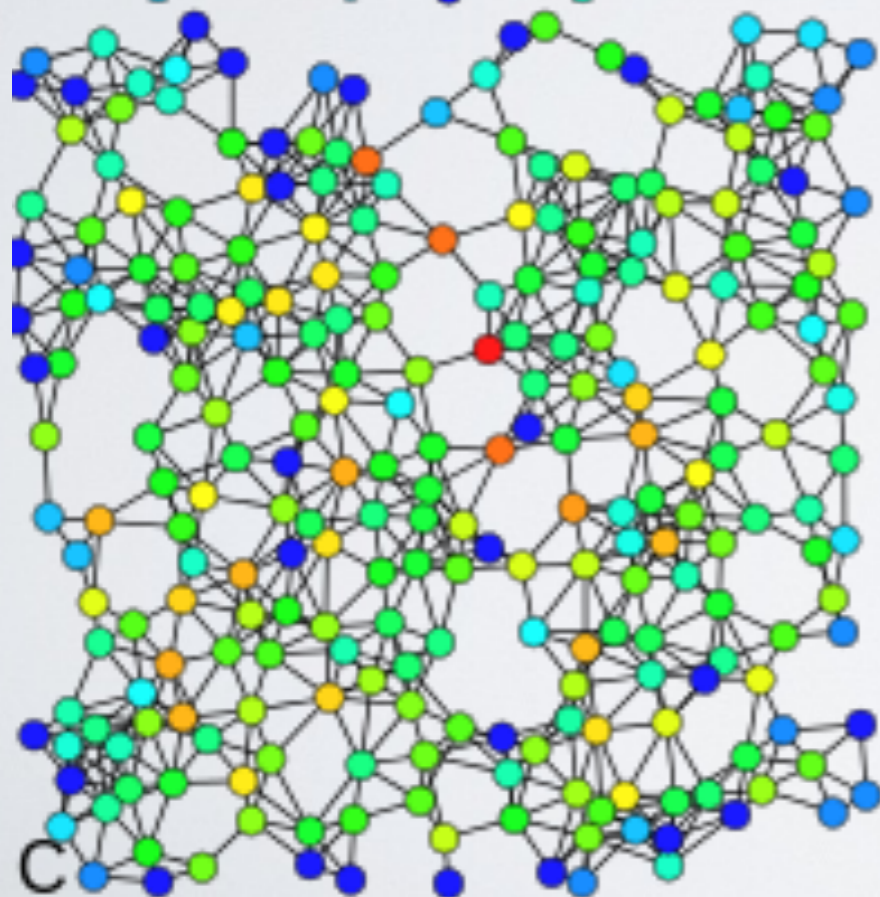
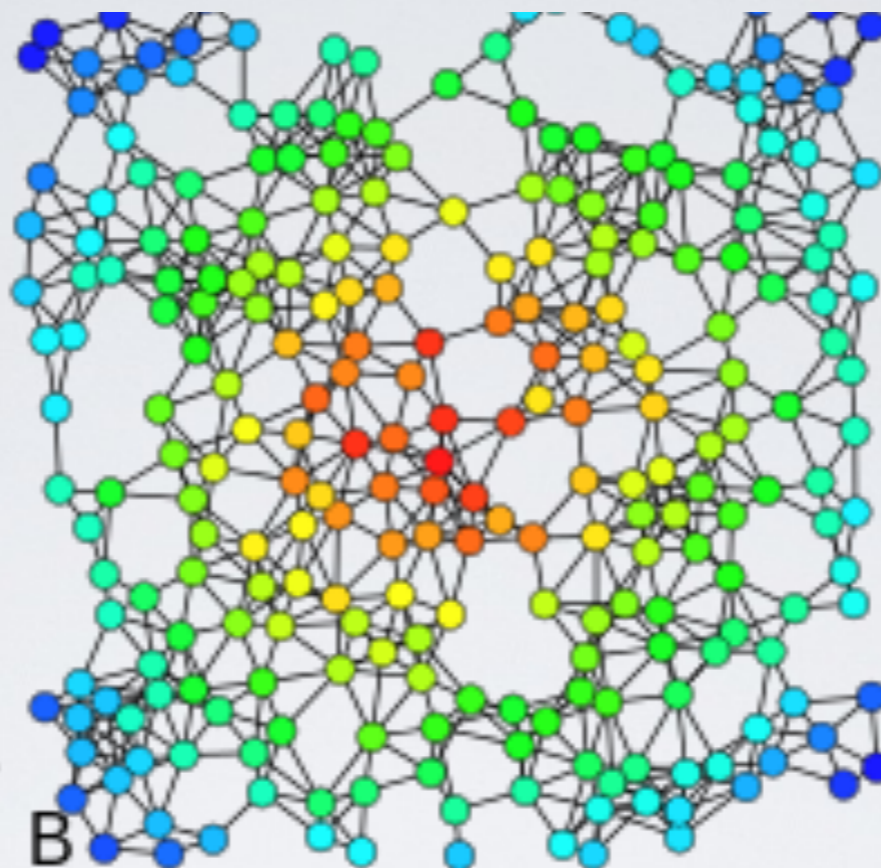
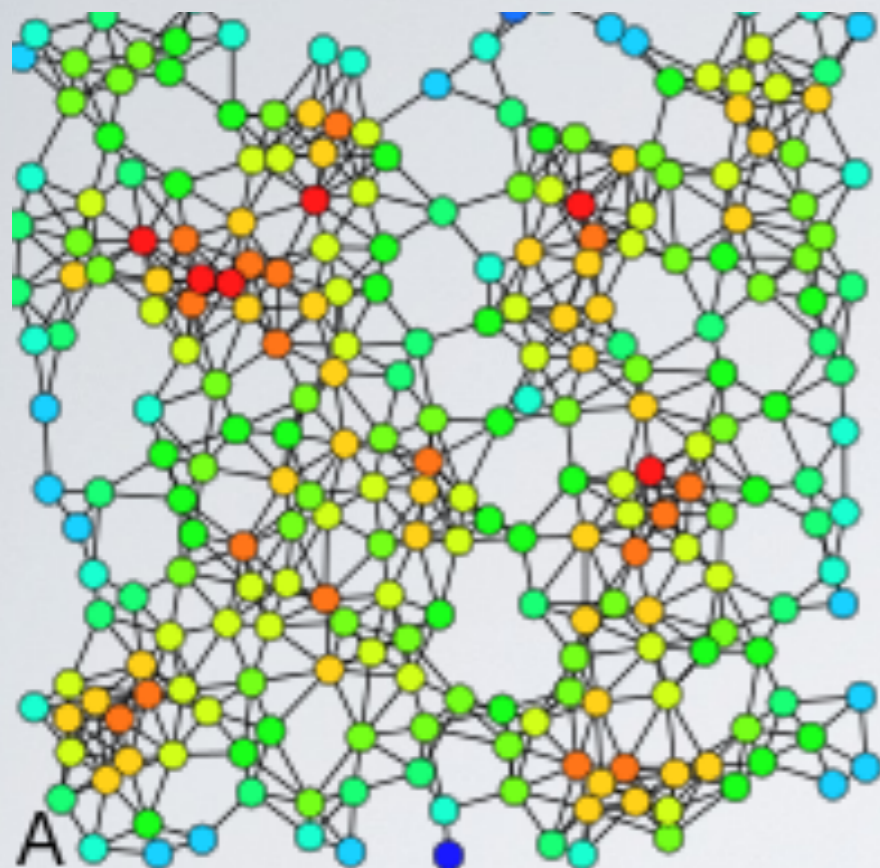


Degree
Clustering coefficient
Closeness
Harmonic Centrality
Betweenness
Katz
Eigenvector
PageRank

Which is which ?

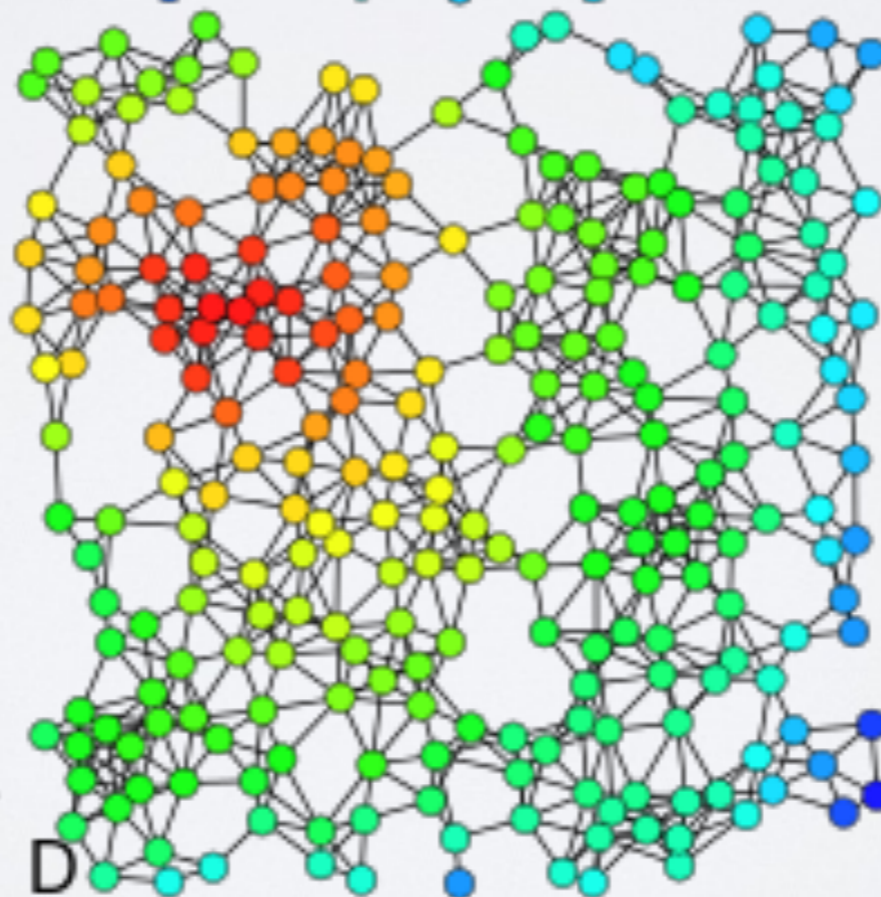
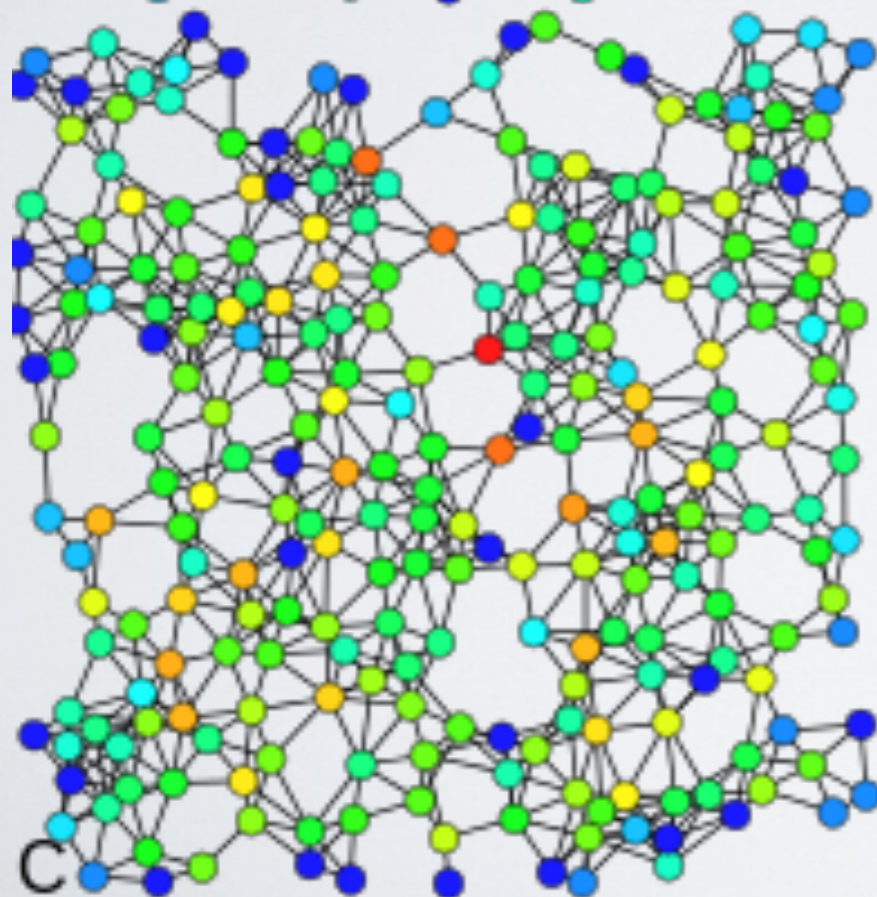
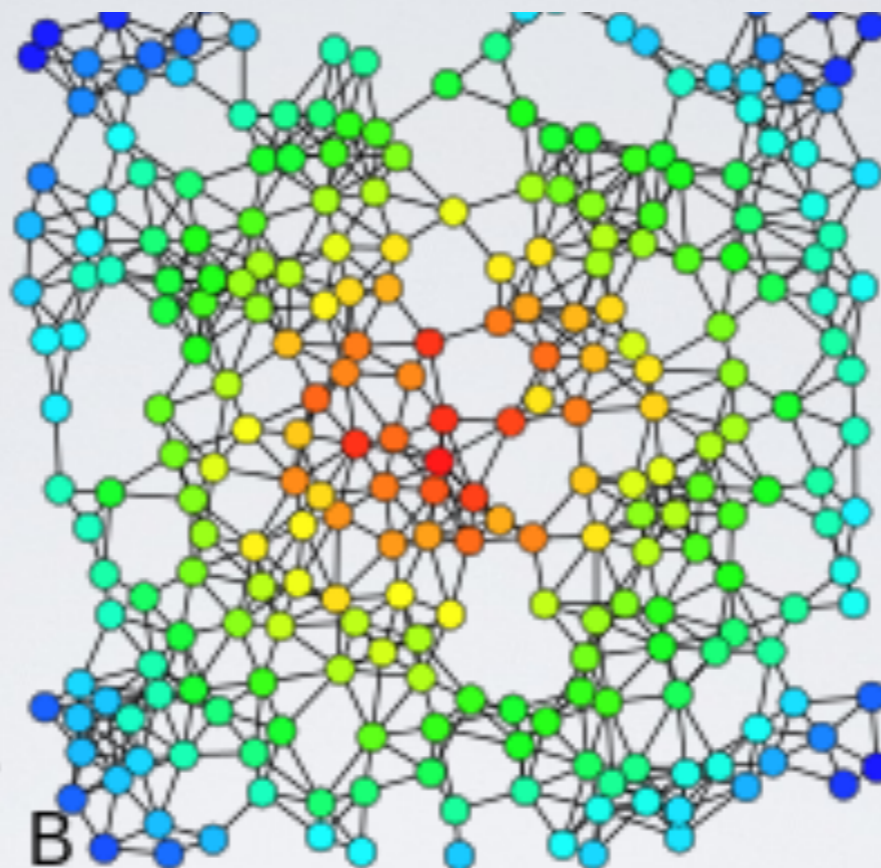
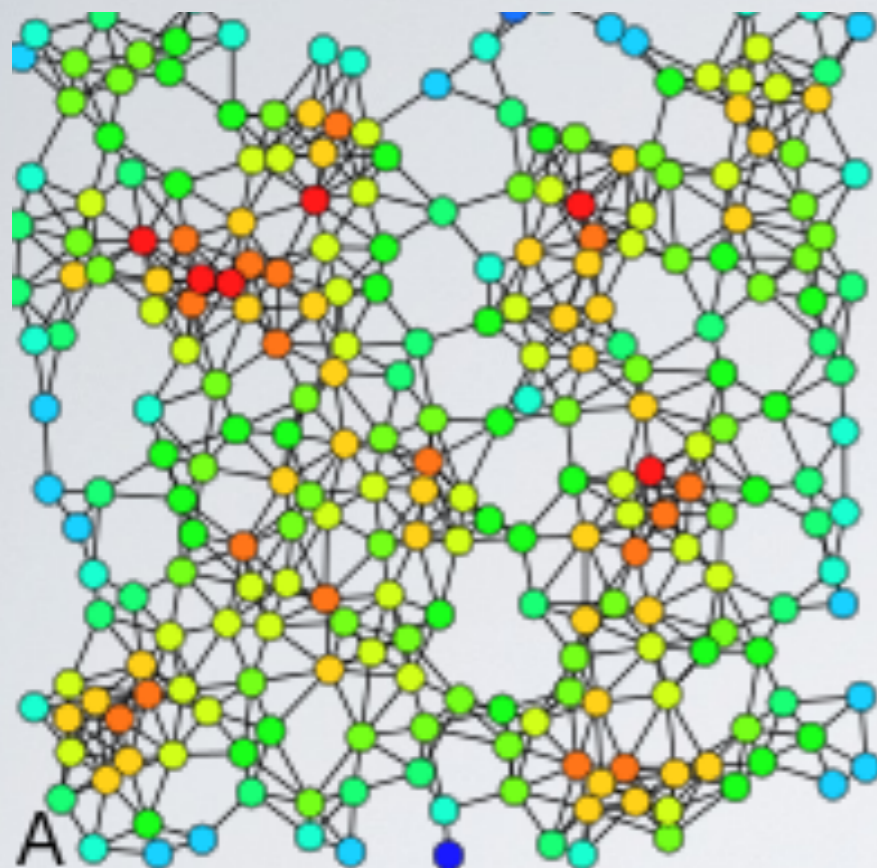


Degree
Clustering coefficient
Closeness
Harmonic Centrality
Betweenness
Katz
Eigenvector
PageRank



Try again :)

Degree
Betweenness
Closeness
Eigenvector



Try again :)

A: Degree

B: Closeness

C: Betweenness

D: Eigenvector

Caveats of centrality measures

- Each centrality measure is a proxy of an underlying network process
- If this process is irrelevant for the actual network then the centrality measure makes no sense
 - *E.g. If information does not pass via the shortest paths in a network, betweenness centrality is irrelevant*

Node similarity

Similarity between nodes based on their neighborhood

How much two nodes are similarly connected

- What does it mean that they have 3 neighbours in common?
- It is relative to their degree (different meaning for nodes with 3 or 100 neighbours)

➔ Normalisation to penalise nodes with small degrees

We can define it using existing measures:

- Cosine Similarity
- Pearson Coefficient

Cosine similarity

Cosine similarity between two non-zero vectors:

$$\cos \theta = \frac{x \cdot y}{|x||y|}$$

Number of common neighbours:

$$n_{ij} = \sum_k A_{ik} A_{kj}$$

Vectors are the rows of adjacency matrix

$$\sigma_{ij} = \cos \theta = \frac{\sum_k A_{ik} A_{kj}}{\sqrt{\sum_k A_{ik}^2} \sqrt{\sum_k A_{jk}^2}}$$

with properties for adjacency vectors as

$$A_{i,j} = 0/1$$

$$A_{ij}^2 = A_{ij}$$

$$\sum_k A_{ik}^2 = \sum_k A_{ik} = k_i$$

Cosine similarity:

$$\sigma_{ij} = \frac{\sum_k A_{ik} A_{kj}}{\sqrt{k_i k_j}} = \frac{n_{ij}}{\sqrt{k_i k_j}}$$

Number of common neighbours normalised by the geometric mean of their degrees

Pearson coefficient

Correlation between rows of the adjacency matrix

$$r_{ij} = \frac{\text{cov}(A_i, A_j)}{\sigma_i \sigma_j} = \frac{\sum_k (A_{ik} - \langle A_i \rangle)(A_{jk} - \langle A_j \rangle)}{\sqrt{\sum_k (A_{ik} - \langle A_i \rangle)^2} \sqrt{\sum_k (A_{jk} - \langle A_j \rangle)^2}}$$

cov: covariance, expected product of deviations from individual expected values
 σ : std deviation, square root of the expected squared deviation from the mean

Intuition, numerator: Number of common neighbours compared to the expected number of common neighbours

$$\sum_k (A_{ik} - \langle A_i \rangle)(A_{jk} - \langle A_j \rangle) = \sum_k A_{ik} A_{jk} - \frac{k_i k_j}{n}$$

Properties

- $r(i,j)=0$ - if the number of common neighbours exactly as many as we would expect by chance
- $r(i,j)>0$ - if nodes have more neighbours in common than expected
- $r(i,j)<0$ - if nodes have fewer neighbours in common than expected

ASSORTATIVITY - HOMOPHILY

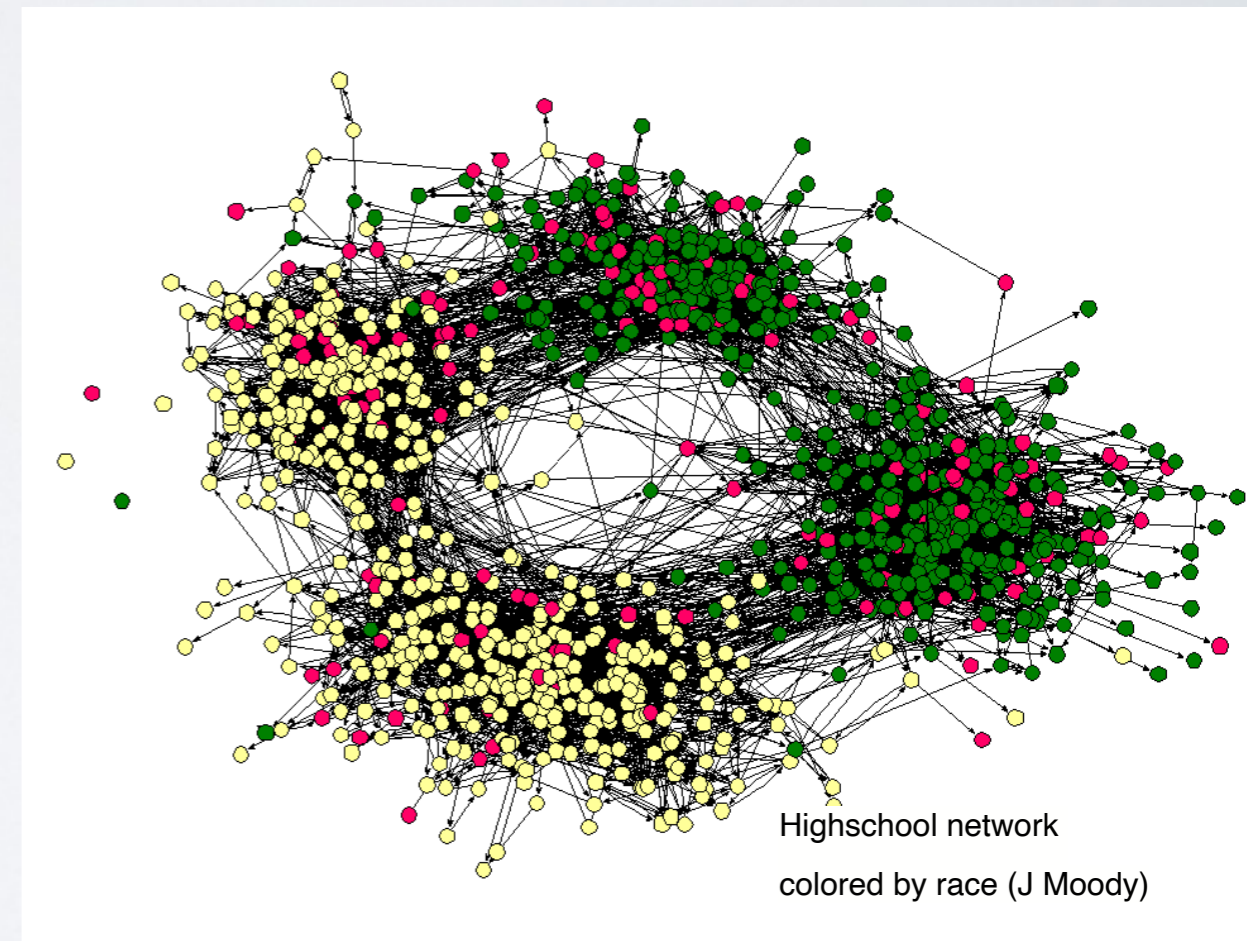
Homophily - Assortative mixing

"birds of a feather flock together"

- Property of (social) networks that nodes of the same attribute tends to be connected with a higher probability than expected
- It appears as correlation between vertex properties of $x(i)$ and $x(j)$ if $(i,j) \in E$

Vertex properties

- age
 - gender
 - nationality
 - political beliefs
 - socioeconomic status
 - habitual place
 - obesity
 - ...
- Homophily can be a link creation mechanism or consequence of social influence (and it is difficult to distinguish)



? Connected people of the same political opinion are connected because they were a priori similar (homophily) or they become similar after they become connected (social influence)?

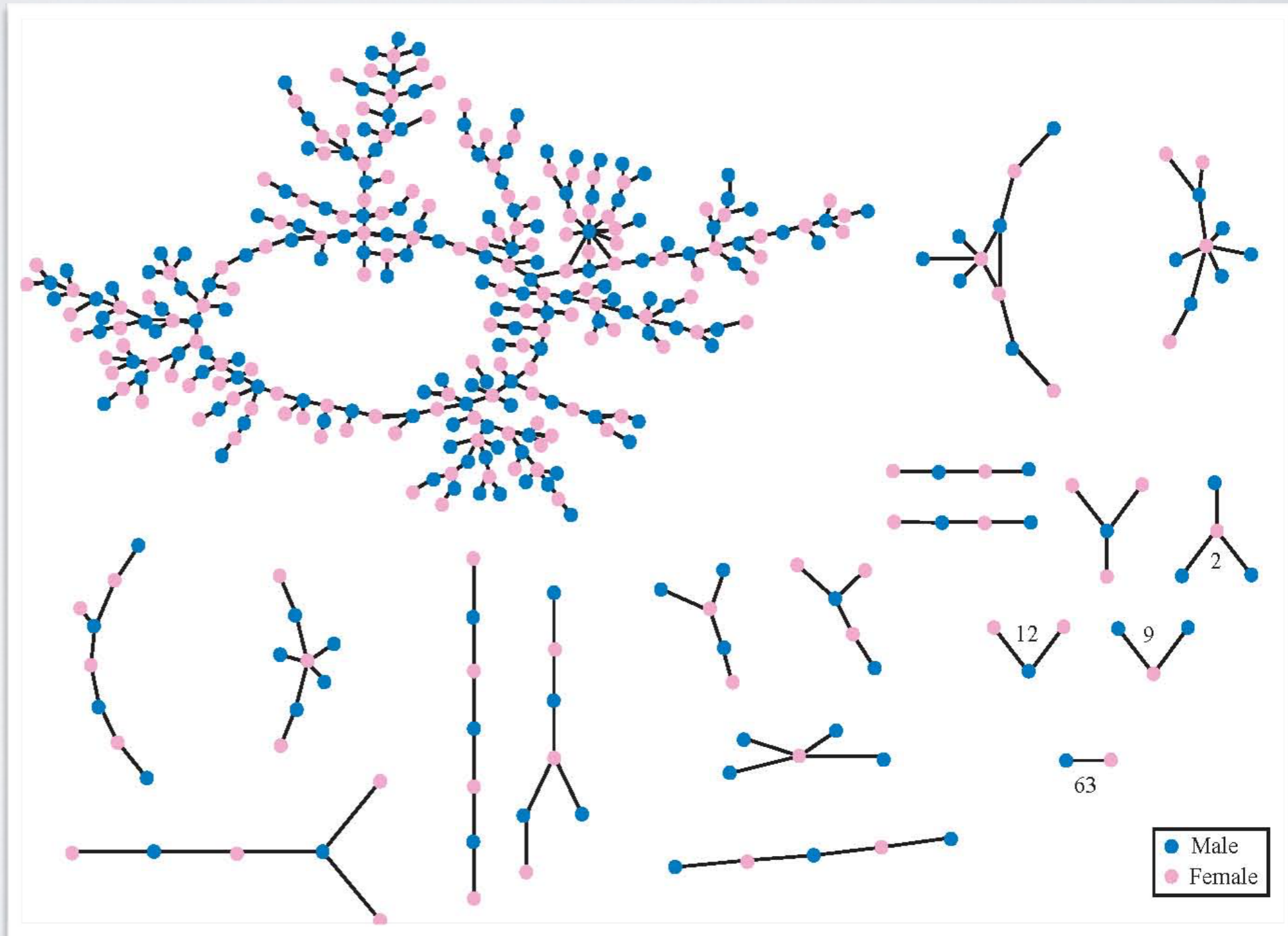
Homophily - Assortative mixing

Dissortative mixing

- Contrary of homophily, where dissimilar nodes are tend to be connected

Examples

- Sexual networks
- Predator - prey ecological networks



Homophily - Assortative mixing

To quantify homophily

Discrete properties

		women				a_i
		black	hispanic	white	other	
men	black	0.258	0.016	0.035	0.013	0.323
	hispanic	0.012	0.157	0.058	0.019	0.247
	white	0.013	0.023	0.306	0.035	0.377
	other	0.005	0.007	0.024	0.016	0.053
b_i		0.289	0.204	0.423	0.084	

TABLE I: The mixing matrix e_{ij} and the values of a_i and b_i for sexual partnerships in the study of Catania *et al.* [23]. After Morris [24].

$$r = \frac{\sum_i e_{ii} - \sum_i a_i b_i}{1 - \sum_i a_i b_i}$$

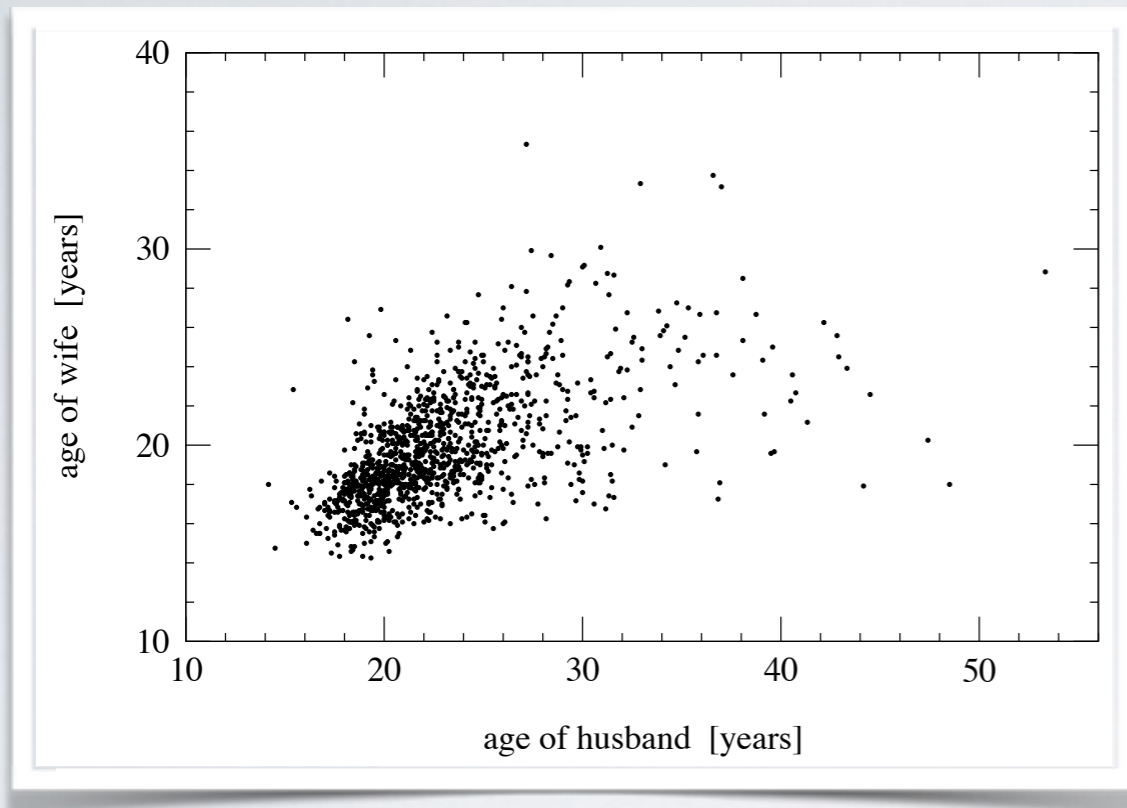
No assortative mixing : $r=0$ ($e_{ij} = a_i b_j$)

Perfectly assortative: $r=1$

Perfectly disassortative: $-1 < r < 0$

Homophily - Assortative mixing

To quantify homophily



Scalar properties

Pearson correlation coefficient of properties at both extremities of edges

e_{xy} : fraction of edges joining nodes with values x and y

$$\sum_{xy} e_{xy} = 1, \quad \sum_y e_{xy} = a_x, \quad \sum_x e_{xy} = b_y$$

$$r = \frac{\sum_{xy} xy(e_{xy} - a_x b_y)}{\sigma_a \sigma_b},$$

with σ_a standard deviation of a_x

$r=0$, no assortative mixing,
 $r>0$ assortative mixing,
 $r<0$ disassortative mixing

Degree-degree correlation

- A particular type of application is the degree correlation:
 - Are *important nodes* connected to other important nodes with a higher probability than expected?
 - The degree can be used as any other scalar property

	network	type	size n	assortativity r	error σ_r
social	physics coauthorship	undirected	52 909	0.363	0.002
	biology coauthorship	undirected	1 520 251	0.127	0.0004
	mathematics coauthorship	undirected	253 339	0.120	0.002
	film actor collaborations	undirected	449 913	0.208	0.0002
	company directors	undirected	7 673	0.276	0.004
	student relationships	undirected	573	-0.029	0.037
	email address books	directed	16 881	0.092	0.004
technological	power grid	undirected	4 941	-0.003	0.013
	Internet	undirected	10 697	-0.189	0.002
	World-Wide Web	directed	269 504	-0.067	0.0002
	software dependencies	directed	3 162	-0.016	0.020
biological	protein interactions	undirected	2 115	-0.156	0.010
	metabolic network	undirected	765	-0.240	0.007
	neural network	directed	307	-0.226	0.016
	marine food web	directed	134	-0.263	0.037
	freshwater food web	directed	92	-0.326	0.031

Average nearest-neighbour degree

R. Pastor-Satorras, A. Vázquez, A. Vespignani, Phys. Rev. E 65, 066130 (2001)

- More detailed characterisation of degree-degree correlations
- k_{annd} : **average nearest neighbours degree**

- k_{annd} can be written as:

$$k_{annd}(k) = \sum_{k'} k' P(k' | k) = \frac{\sum_{k'} k' e_{kk'}}{\sum_{k'} e_{kk'}}$$

- where $P(k' | k)$ is the conditional probability that an edge of a node with degree k points to a node with degree k'
- If there are no degree correlations:

$$k_{annd}(k) = \dots = \frac{\langle k^2 \rangle}{\langle k \rangle}$$

- k_{annd} is independent of k (nodes of any degrees should have the same nearest neighbors degree)
- If the network is **assortative** $k_{nn}(k)$ is a **positive function**
- If the network is **disassortative** $k_{nn}(k)$ is a **negative function**